

Unitarity Constraints for New Physics Induced by dim-6 Operators[†]

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Abstract

We compute the helicity amplitudes for boson-boson scattering at high energy due to the operators $\mathcal{O}_{B\Phi}$, $\mathcal{O}_{W\Phi}$ and \mathcal{O}_{UB} , and we derive the corresponding unitarity bounds. Thus, we provide relations between the couplings of these operators and the corresponding New Physics thresholds, where either unitarity is saturated or new degrees of freedom are excited. We compare the results with those previously obtained for the operators \mathcal{O}_W and \mathcal{O}_{UW} and we discuss their implications for direct and indirect tests at present and future colliders. The present treatment completes the study of the unitarity constraints for all blind bosonic operators.

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1 Introduction

At present energies where no production of any New Physics (NP) particles has ever been observed, the search of NP effects goes mainly through the procedure dubbed high precision tests [1]. It corresponds to the hypothesis that NP dynamics is governed by a characteristic scale Λ_{NP} lying much above the electroweak scale v . Therefore its observable effects in present high precision experiments should take the form of residual interactions among usual particles (leptons, quarks, gauge bosons and possibly Higgs bosons), which are beyond those expected in the Standard Model (SM). Such residual interactions can be described in terms of effective lagrangians.

These effective Lagrangians are constructed [2] in terms of standard model fields and are constrained to preserve the usual space-time and internal symmetries of the SM. Thus $SU(2) \times U(1)$ gauge invariance is imposed, which has the extra benefit that it tempers the loop divergences and leads to a decent Λ_{NP} dependence of loop integrals involving these interactions [3, 4]. However this does not restrict by itself the number of independent NP operators [5]. Such a restriction is generated though from the fact that $\Lambda_{NP} \gg v$, which hopefully means that only a few low dimensional operators are relevant. Since SM already includes all possible $dim = 4$ terms, the NP effects start being described by the $dim = 6$ operators.

A restricted list of effective lagrangians has been established on the basis of the results of the high precision tests performed at LEP1, SLC and other low energy experiments [6]. Indeed, from the absence of any departure from the SM predictions in fermionic interactions (at the permille level in some cases), it seems natural to describe the NP effects using operators involving only the bosonic fields (γ , Z, W, H). Imposing also CP invariance for NP, a list of 11 independent $dim = 6$ bosonic operators has been drawn [4]. Four of these operators, however, affect the gauge boson 2-point functions at tree level and their contribution is severely constrained by the high precision tests. Another two depend only on Higgs fields and do not lead to any observable effects in present or future experiments. Consequently, we end up with five remaining operators (the so called "blind" operators [3]), which are viable candidates for the description of observable NP effects in the near future. These operators imply genuine NP gauge boson and Higgs self interactions, involving 3-boson and multi-boson vertices. These NP manifestations could be observable at future machines through gauge boson pair production as well as through production of channels involving Higgs bosons.

It has been shown that if LEP1 high precision measurements are used to test the indirect 1-loop contributions of these operators to the gauge boson self-energies, then the constraints obtained on their couplings are rather mild [4]. Therefore considerable room exists at present, for the observability of such interactions at LEP2 [7] (at the level of $O(0.1)$) and a fortiori also at the higher energy machines LHC [8] and NLC [9], [10], where the sensitivity should be 10 to 100 times better. Further restrictions on these operators may be found by making dynamical assumptions on the origin of NP and the additional symmetries that it might satisfy [11, 12, 13].

In this paper we discuss the validity domain of these operators by using unitarity

constraints. This is amply motivated by the fact that at least in the well known old example of the Fermi current-current interaction (which is also a $dim = 6$ operator), unitarity considerations have proven to be extremely powerful in pinpointing the correct energy region where the underlying new physics would arise; *i.e.* the M_W , M_Z mass domain.

In a similar way, the above NP local operators lead to amplitudes involving the various gauge bosons and Higgs particles, which approach the unitarity limit at a sufficiently high energy. Thus, either strong interactions will be generated at such an energy, or new particles will be excited which will destroy the locality of the NP operators we have started with¹. This energy value should be identified with the NP scale or threshold Λ_{NP} . So for each of the five blind operators, unitarity considerations provide relations between their coupling constants and the NP scale. These relations can be used in several ways. Thus, if from some model one knows a lower bound for the NP scale Λ_{NP} , then unitarity can be used to obtain upper bounds for the couplings of the various NP operators. Or vice versa, if an upper bound on any of these couplings is experimentally established, then unitarity provides a lower bound for the relevant NP threshold Λ_{NP} . Obviously a very accurate experiment, sensitive to very small couplings, will be able to push Λ_{NP} to very high values.

In a previous paper [14] we established such relations for two of the above blind operators. These operators were selected because they are also invariant under custodial $SU(2)_c$ transformations. They have the common property of generating at sufficient high energies, strong interactions among transverse W_T states, irrespective of the Higgs mass. This was a novel feature as compared to the well-known case [15] of strong interactions appearing among longitudinal W_L states in the $M_H \rightarrow \infty$ limit. We now extend this program to the full set of blind operators. One of them (\mathcal{O}_{UB}) can also generate strong interactions for transverse B_T states, whereas ($\mathcal{O}_{W\Phi}$ and $\mathcal{O}_{B\Phi}$) affect strongly the longitudinal W_L and B_L states also. In this last case though, the situation is different from the usual one in [15], because now strong interactions appear even if the Higgs boson is so light that it can possibly also be produced [16].

We established these unitarity relations by following a 3-step procedure. Firstly, we compute all 2-body boson-boson helicity amplitudes involving γ , Z , W and H states, generated by any blind operator. Very simple expressions for these amplitudes are obtained for c.m. above 1 TeV , by neglecting all subleading $O(M_W^2/s)$ terms [8]. These results should, by the way, be useful for computing the various observables in boson-boson fusion processes at high energy colliders. Secondly, we project these high energy amplitudes on the lowest partial waves which give the most stringent unitarity constraints. And thirdly, we derive the unitarity limit for each partial wave by diagonalizing the related matrix, thus getting relations between the coupling constants and the energy scale. As explained in [14], it is justified for our indicative purposes to treat each blind operator separately. The results for the various operators are discussed and compared with the indirect constraints obtained from high precision tests, and with the sensitivities expected at future machines.

¹In fact this is what happened to the old Fermi theory.

We will see that this is instructive for scrutinizing the NP properties and identifying the sector where they are originated.

The development of the paper goes through the 3 steps mentioned above. In Sect. 2 we present the various 2-body scattering helicity amplitudes whose high energy expressions are explicitly written in Appendix A and B. In Sect. 3 we project the partial waves and write the unitarity constraints for the three new operators. A discussion of the results and a comparison with other constraints is done in Sect. 4. Their implications for the search of NP are drawn in the concluding Sect. 5.

2 Boson-boson scattering through $dim = 6$ interactions

We derive the full set of vector boson ($V = \gamma, Z, W^\pm$) and Higgs boson (H) scattering amplitudes in the VV , HV and HH channels, due to the three blind operators

$$\mathcal{O}_{B\Phi} = iB^{\mu\nu}(D_\mu\Phi)^\dagger D_\nu\Phi \quad , \quad (1)$$

$$\mathcal{O}_{W\Phi} = i\vec{W}^{\mu\nu} \cdot (D_\mu\Phi)^\dagger \vec{\tau} D_\nu\Phi \quad , \quad (2)$$

$$\mathcal{O}_{UB} = \frac{2}{v^2} \langle \hat{U}\hat{U}^\dagger - \frac{v^2}{2} \rangle B_{\mu\nu} B^{\mu\nu} \quad , \quad (3)$$

where $\vec{W}^{\mu\nu}$ is the non-abelian W field strength and \hat{U} is the scalar field matrix

$$\hat{U} = (\begin{smallmatrix} \tilde{\Phi} & \Phi \end{smallmatrix}) \quad , \quad (4)$$

$$\Phi = \left(\begin{smallmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + H + i\phi^0) \end{smallmatrix} \right) \quad , \quad (5)$$

$\tilde{\Phi} = i\tau_2\Phi^*$, $\langle A \rangle \equiv Tr A$ and $v = 2M_W/g_2$.

These processes go through vector and Higgs boson exchange as well as 4- particle contact terms. The NP Lagrangian is written as

$$\mathcal{L}_{NP} = \frac{f_B g_1}{2M_W^2} \mathcal{O}_{B\Phi} + \frac{f_W g_2}{2M_W^2} \mathcal{O}_{W\Phi} + \frac{d_B}{4} \mathcal{O}_{UB} + \lambda_W \frac{g_2}{M_W^2} \mathcal{O}_W + d \mathcal{O}_{UW} \quad , \quad (6)$$

where we have also included for later convenience the contribution from the blind operators \mathcal{O}_W and \mathcal{O}_{UW}

$$\mathcal{O}_W = \frac{1}{3!} \left(\vec{W}_\mu^\nu \times \vec{W}_\nu^\lambda \right) \cdot \vec{W}_\lambda^\mu \quad , \quad (7)$$

$$\mathcal{O}_{UW} = \frac{1}{2v^2} \langle \hat{U}\hat{U}^\dagger - \frac{v^2}{2} \rangle \vec{W}_{\mu\nu} \cdot \vec{W}^{\mu\nu} \quad , \quad (8)$$

analysed in [14]. The implied Feynman rules are given in Table I.

The explicit expressions of the helicity amplitudes in the high energy approximation are given in Appendix A for the $\mathcal{O}_{B\Phi}$ and $\mathcal{O}_{W\Phi}$ contributions, and in Appendix B for the \mathcal{O}_{UB} case. At the tree level we are working in, we only have linear and quadratic terms in the new couplings f_B , f_W , d_B . They grow with energy like s , $s^{3/2}$ or s^2 . The leading SM contributions can be found in [8], and the results for the other blind operators \mathcal{O}_W and \mathcal{O}_{UW} are listed in [8, 16]. Subleading terms are suppressed by powers of M_W^2/s compared to the leading ones and they are negligible for $s \gtrsim 1 \text{ TeV}^2$. Thus these amplitudes are very accurate for energies $\gtrsim 1 \text{ TeV}$.

In the $\mathcal{O}_{B\Phi}$ and $\mathcal{O}_{W\Phi}$ cases, the unitarity limits are reached when quantities of the type $(fs/M_W^2)^2$ are large. As we are obviously interested in scales $s \gg M_W^2$, the other possible terms, (of the form f^2s/M_W^2 or fs/M_W^2), are negligible. This simplifies very much the calculation, since the leading contribution arises from just the three neutral channels $W_L^-W_L^+$, Z_LZ_L and HH , which in turn means that we only have to diagonalize a 3×3 matrix.

In the \mathcal{O}_{UB} case, the leading contributions can be either of the form d_Bs/M_W^2 arising from $SM - \mathcal{O}_{UB}$ interference in LLTT and HHTT channels, or of the form d_B^2s/M_W^2 due to purely transverse amplitudes involving two \mathcal{O}_{UB} vertices. This fact increases somewhat the rank of the matrix to be diagonalized in this case, and it is similar to the situation observed in the \mathcal{O}_{UW} treatment [14]. We also remark that \mathcal{O}_{UB} generates strong interactions involving mainly B_T and H , whereas the strong interactions induced by $\mathcal{O}_{W\Phi}$ and $\mathcal{O}_{B\Phi}$ affect more the W_L , B_L and H states.

3 Partial wave unitarity limits

We project to partial waves the high energy helicity amplitudes gotten in the previous Section according to the expansion [17]

$$F(\lambda_1\lambda_2 \rightarrow \lambda_3\lambda_4) = 16\pi \sum_j \left(j + \frac{1}{2}\right) D_{\lambda_1-\lambda_2, \lambda_3-\lambda_4}^{j*}(\phi, \theta, 0) \langle \lambda_3\lambda_4 | T^j | \lambda_1\lambda_2 \rangle \quad , \quad (9)$$

for which the unitarity constraint is

$$|T^j| \leq 2 \quad . \quad (10)$$

The most stringent constraints come from the lowest values of the total angular momentum j . They are obtained by separately treating the sectors with total charge in the s-channel $Q = 2, 1, 0$.

In the $Q = 2$ sector (*i.e.* the channel W^+W^+), the most stringent constraint is derived from the $j = 0$ amplitude predominantly involving only $|W^+W^+LL\rangle$ state. From these we obtain

$$|f_B| \lesssim 101 \frac{M_W^2}{s} \quad , \quad |f_W| \lesssim 58 \frac{M_W^2}{s} \quad . \quad (11)$$

The $Q = 1$ sector contains the channels γW , ZW and HW which can interact through all three types of operators. In the case of $\mathcal{O}_{W\Phi}$ and $\mathcal{O}_{B\Phi}$, the most important $j = 0$

partial amplitude relates the 6 states ($|ZW \pm \pm\rangle$, $|ZWLL\rangle$, $|\gamma W \pm \pm\rangle$, $|HWL\rangle$) giving the unitarity bounds are

$$|f_B| \lesssim 98 \frac{M_W^2}{s} \quad , \quad |f_W| \lesssim 54 \frac{M_W^2}{s} \quad . \quad (12)$$

No $j = 0$ amplitude involving \mathcal{O}_{UB} appears in the $Q = 1$ sector. So, we have to consider the $j = 1$ amplitudes. However these only contain terms linear in d_B , so that the bound is rather weak

$$|d_B| \lesssim 768 \frac{M_W^2}{s} \quad . \quad (13)$$

The $Q = 0$ (neutral) sector is the richest one. $\mathcal{O}_{B\Phi}$ and $\mathcal{O}_{W\Phi}$ contribute to the 12 $j = 0$ states, ($|\gamma\gamma \pm \pm\rangle$, $|\gamma Z \pm \pm\rangle$, $|HZZ\rangle$, $|W^-W^+ \pm \pm\rangle$, $|W^-W^+LL\rangle$, $|ZZ \pm \pm\rangle$, $|ZZLL\rangle$, $|HH\rangle$). From the diagonalization of this $j = 0$ amplitude we get

$$|f_B| \lesssim 98 \frac{M_W^2}{s} \quad , \quad |f_W| \lesssim 31 \frac{M_W^2}{s} \quad . \quad (14)$$

For the \mathcal{O}_{UB} case, the 9 states ($|\gamma\gamma \pm \pm\rangle$, $|\gamma Z \pm \pm\rangle$, $|ZZ \pm \pm\rangle$, $|ZZLL\rangle$, $|W^-W^+LL\rangle$, $|HH\rangle$) are the ones which predominantly participate in the $j = 0$ partial amplitude. From its diagonalization we get

$$\frac{\alpha d_B s}{4M_W^2} (\sqrt{33d_B^2 + 16d_B + 8} - d_B) \lesssim 1 \quad , \quad (15)$$

whose numerical solution for $s \gtrsim 1 \text{ TeV}^2$ is

$$-236 \frac{M_W^2}{s} + 1070 \frac{M_W^3}{s^{3/2}} \lesssim d_B \lesssim 192 \frac{M_W^2}{s} - 1123 \frac{M_W^3}{s^{3/2}} \quad . \quad (16)$$

For $\alpha s/M_W^2 \gg 1 \text{ TeV}^2$ (i.e. $s \gtrsim 10 \text{ TeV}^2$) this result simplifies to

$$|d_B| \lesssim 180 \frac{M_W^2}{s} \quad . \quad (17)$$

.

4 Panorama of unitarity constraints.

The most stringent results found above are

$$|f_B| \leq 98 \frac{M_W^2}{s} \quad , \quad |f_W| \leq 31 \frac{M_W^2}{s} \quad , \quad (18)$$

and eqs. (16, 17) for d_B . Together with these we recall the corresponding unitarity constraints on \mathcal{O}_W and \mathcal{O}_{UW} derived in [14]

$$|\lambda_W| \lesssim 19 \frac{M_W^2}{s} \quad , \quad |d| \lesssim 17.6 \frac{M_W^2}{s} + 2.43 \frac{M_W}{\sqrt{s}} \quad ; \quad (19)$$

(compare (6)). We now discuss the unitarity bounds obtained for all five blind operators.

The bound on f_B is somewhat weaker than the other ones, because of its normalization through the smaller value of g_1 rather than that of g_2 . Recall the definition of these couplings given in (6). The bound (16, 17) for d_B is also somewhat weaker than the one for d in (19). This can be understood from the definitions (3, 8) of the corresponding operators, by remarking that there is no HWW coupling through d_B , while the HZZ coupling induced by d_B is weaker than the d induced one by a factor of s_W^2/c_W^2 ; (note that the role of ZZ and $\gamma\gamma$ are interchanged when passing from d to d_B). We also remark that this d_B versus d comparison would have been more striking if we had not used the factors of two in the definitions (3, 8).

In practice, assuming a certain value for the NP scale $s = \Lambda_{NP}^2$, one deduces upper bounds for the various couplings. For example if $\Lambda_{NP} = 1 \text{ TeV}$ one obtains

$$|f_B| \lesssim 0.6 \quad , \quad |f_W| \leq 0.2 \quad , \quad -0.8 \lesssim d_B \lesssim 0.6 \quad , \quad (20)$$

$$|\lambda_W| \lesssim 0.12 \quad , \quad |d| \lesssim 0.3 \quad . \quad (21)$$

These relations provide a feeling of how sensitive the various couplings are to unitarity constraints. Conversely, from the expected sensitivities to these couplings at future colliders, one can deduce the achievable lower bounds for the NP scale Λ_{NP} at these machines; *i.e.* the lower bound for either the generation of new strong interactions, or the production of new particles. For example at NLC (0.5 TeV) where the observability limits can be written as [9]

$$|f_B| \gtrsim 0.012 \quad , \quad |f_W| \gtrsim 0.006 \quad , \quad (22)$$

we expect to be sensitive to NP scales satisfying

$$\Lambda_{NP}(f_B) \lesssim 7 \text{ TeV} \quad , \quad \Lambda_{NP}(f_W) \lesssim 6 \text{ TeV} \quad , \quad (23)$$

to be compared to

$$\Lambda_{NP}(\lambda_W) \lesssim 4 \text{ TeV} \quad , \quad (24)$$

obtained from $|\lambda_W| \gtrsim 0.008$ [9].

We next turn to the Higgs sector. For \mathcal{O}_{UW} , the highest sensitivity $|d| \gtrsim 0.001$ was obtained from $\gamma\gamma \rightarrow H$ production in laser backscattering experiments [16]. This implies

$$\Lambda_{NP}(d) \leq 30 \text{ TeV} \quad . \quad (25)$$

In the \mathcal{O}_{UB} case the $\gamma\gamma \rightarrow H$ production rate is enhanced by the factor c_W^2/s_W^2 . From statistics one then expects an increase in sensitivity by a factor 3, which means $|d_B| \gtrsim 3.10^{-4}$, and from eq(16, 17)

$$\Lambda_{NP}(d_B) \lesssim 60 \text{ TeV} \quad . \quad (26)$$

5 Implications for New Physics searches

We have established unitarity constraints for effective interactions which turn out to have many implications. They give relations between the coupling constants of each blind operator and the related NP scale at which new phenomena should appear. For example, assuming that the NP scale (or a lower bound of this) is known, one obtains an upper bound for the various couplings. Thus if *e.g.* $\Lambda_{NP} \gtrsim 1 \text{ TeV}^2$, then $|f_B| \lesssim 0.6$, $|f_W| \lesssim 0.2$, $|\lambda_W| \lesssim 0.12$, $-0.8 \lesssim d_B \lesssim 0.6$ and $|d| \lesssim 0.3$. Such bounds are quite interesting. They lie in the same range as those obtained by calculating the indirect 1-loop effects of the blind operators using the LEP1 constraints [3, 4]. However, when doing such 1-loop computations with blind operators, one should remember that the NP contributions in the energy range $s \gtrsim \Lambda_{NP}^2$ are actually ignored, while the lower energies contribute. For the validity of such calculations, it should therefore be checked, a posteriori, whether strong interactions have not already been developed in the energy range affecting the result. It is obvious that in the later case the perturbative treatment would be questioned. Moreover, the only way to justify ignoring the contributions from a strongly interacting energy regime is to assume that somehow the theory softens there. More concretely, one should worry whether such a treatment is justified in case the values of the coupling constants obtained and the NP scales assumed, violate our unitarity relations.

Another aspect of our unitarity constraints is to associate in a simple way the NP scale to the observability limits which could be established for each effective interaction at future colliders. In that way one can clearly see that LEP2 experiments could explore the TeV range Λ_{NP} , while the LHC and NLC ones should be sensitive to NP at scales up to several tens of TeV.

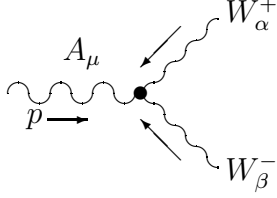
It is then interesting to examine more carefully the structure of the effective operators and the nature of the NP effects involved. In the former cases [14] of \mathcal{O}_W and \mathcal{O}_{UW} , as well as in the \mathcal{O}_{UB} case treated in this paper, strong interactions appear among transverse gauge boson (W_T , Z_T , γ_T) and Higgs states. The two other operators $\mathcal{O}_{W\Phi}$ and $\mathcal{O}_{B\Phi}$ generate strong interactions mainly among longitudinal W_L , B_L and Higgs states. Note that contrary to the SM case for which strong W_L interactions appear in the $M_H \rightarrow \infty$ limit, here it is not necessary for the Higgs mass to be large. These strong interactions appear even when the Higgs boson is light, and this light Higgs is itself strongly coupled to either W_T , B_T or W_L , B_L states. This means that each class of effective operators has a different implication about the NP properties and their origin. It is then extremely useful to disentangle these various possible NP manifestations in experimental measurements, or to precisely determine the observability limits for each of these new interactions separately. This will allow to test the NP pictures that one can have in mind, or at least to discriminate among the various sectors from which NP can originate.

Acknowledgements

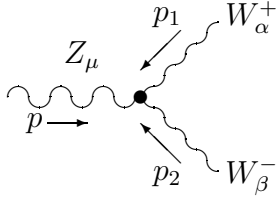
One of us (F.M.R.) wishes to thank the Department of Theoretical Physics of the University of Thessaloniki for the warm hospitality as well as the kind help that he received during his stay and for the creative atmosphere that was generated during the preparation of this paper.

Table I: Feynman rules for $\mathcal{O}_{W\Phi}$, $\mathcal{O}_{B\Phi}$ and \mathcal{O}_{UB} interactions

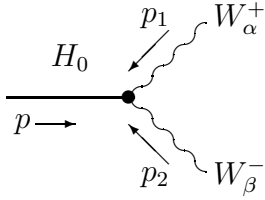
From the NP Lagrangian of eq(6) in the unitary-gauge, one derives the following expressions for the 3- and 4- body vertices



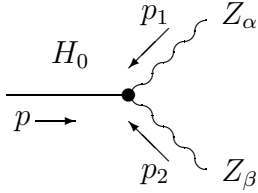
$$\frac{i}{2}(g_2 f_W \sin \theta_W + g_1 f_B \cos \theta_W)(p_\beta g_{\mu\alpha} - p_\alpha g_{\mu\beta})$$



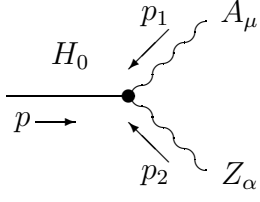
$$\frac{-ig_2 f_W}{2 \cos \theta_W} \{p_{1\beta} g_{\alpha\mu} - p_{1\mu} g_{\alpha\beta} - p_{2\alpha} g_{\beta\mu} + p_{2\mu} g_{\alpha\beta}\} \\ + \frac{i}{2}(g_2 f_W \cos \theta_W - g_1 f_B \sin \theta_W)(p_\beta g_{\mu\alpha} - p_\alpha g_{\mu\beta})$$



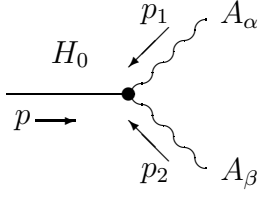
$$\frac{ig_2 f_W}{2M_W} \{g_{\alpha\beta} p \cdot (p_1 + p_2) - p_\alpha p_{1\beta} - p_\beta p_{2\alpha}\}$$



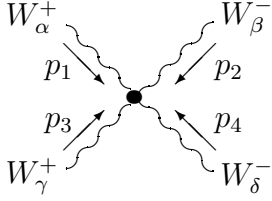
$$\frac{i}{2M_W} [(g_2 f_W + g_1 f_B \tan \theta_W) \{g_{\alpha\beta} p \cdot (p_1 + p_2) - \\ p_\alpha p_{1\beta} - p_\beta p_{2\alpha}\} \\ - 4 d_B g_2 \sin^2 \theta_W \{g_{\alpha\beta} p_1 \cdot p_2 - p_{1\beta} p_{2\alpha}\}]$$



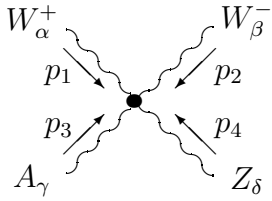
$$\frac{i}{2M_W} [(g_2 f_W \tan \theta_W - g_1 f_B) \{ g_{\mu\alpha} (p \cdot p_1) - p_\mu p_{1\alpha} \} + 4 d_B g_2 \sin \theta_W \cos \theta_W \{ g_{\mu\alpha} p_1 \cdot p_2 - p_{2\mu} p_{1\alpha} \}]$$



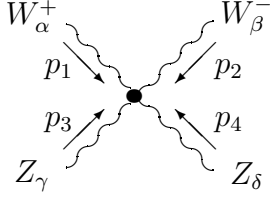
$$- \frac{2i d_B g_2 \cos^2 \theta_W}{M_W} \{ g_{\alpha\beta} p_1 \cdot p_2 - p_{1\beta} p_{2\alpha} \}$$



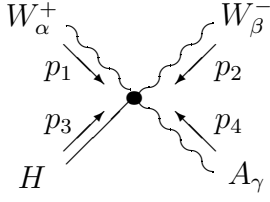
$$i g_2 f_W g_2 \{ 2g_{\alpha\gamma} g_{\beta\delta} - g_{\alpha\beta} g_{\gamma\delta} - g_{\alpha\delta} g_{\beta\gamma} \}$$



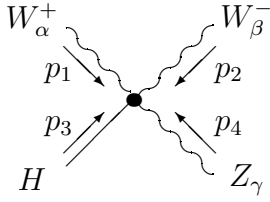
$$\frac{-i g_2 f_W}{2} \sin \theta_W (g_2 \cos \theta_W + g_1 \sin \theta_W) \{ 2g_{\alpha\beta} g_{\gamma\delta} - g_{\alpha\gamma} g_{\beta\delta} - g_{\alpha\delta} g_{\beta\gamma} \}$$



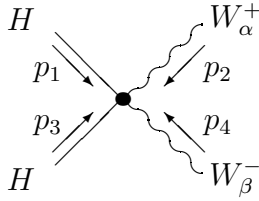
$$-ig_2 f_W \cos \theta_W (g_2 \cos \theta_W + g_1 \sin \theta_W) \{2g_{\alpha\beta}g_{\gamma\delta} - g_{\alpha\delta}g_{\gamma\beta} - g_{\alpha\gamma}g_{\beta\delta}\}$$



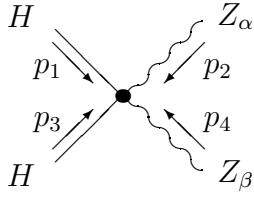
$$\frac{ig_2^2 f_W}{2M_W} \sin \theta_W (p_{3\alpha}g_{\beta\gamma} - p_{3\beta}g_{\alpha\gamma}) + \frac{ig_2}{2M_W} (g_2 f_W \sin \theta_W + g_1 f_B \cos \theta_W) (p_{4\beta}g_{\alpha\gamma} - p_{4\alpha}g_{\beta\gamma})$$



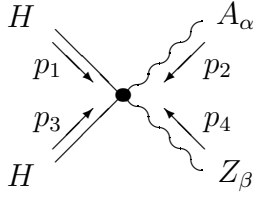
$$\frac{ig_2 f_W}{2M_W} \{ (g_2 \cos \theta_W + g_1 \sin \theta_W) [(p_{2\alpha}g_{\beta\gamma} - p_{2\gamma}g_{\alpha\beta} - p_{1\beta}g_{\alpha\gamma} + p_{1\gamma}g_{\alpha\beta}) + g_1 \sin \theta_W (p_{3\beta}g_{\alpha\gamma} - p_{3\alpha}g_{\beta\gamma})] \} + \frac{ig_1}{2M_W} (g_2 f_W \cos \theta_W - g_1 f_B \sin \theta_W) [p_{4\beta}g_{\alpha\gamma} - p_{4\alpha}g_{\beta\gamma}]$$



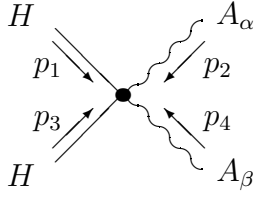
$$\frac{-ig_2 f_W}{4M_W^2} g_1 \{ p_{2\beta} p_{1\alpha} - p_1 \cdot p_2 g_{\alpha\beta} + p_{1\beta} p_{4\alpha} - p_1 \cdot p_4 g_{\alpha\beta} + p_{2\beta} p_{3\alpha} - p_2 \cdot p_3 g_{\alpha\beta} + p_{3\beta} p_{4\alpha} - p_4 \cdot p_3 g_{\alpha\beta} \}$$



$$\frac{-i}{4M_W^2} [(g_2 f_W \cos \theta_W + g_1 f_B \sin \theta_W)(g_1 \cos \theta_W + g_2 \sin \theta_W) \\ \{ p_{2\beta} p_{3\alpha} - p_3 \cdot p_2 g_{\alpha\beta} + p_{3\beta} p_{4\alpha} - p_3 \cdot p_4 g_{\alpha\beta} + p_{2\beta} p_{1\alpha} - \\ p_2 \cdot p_1 g_{\alpha\beta} + p_{1\beta} p_{4\alpha} - p_1 \cdot p_4 g_{\alpha\beta} \} \\ + 16 d_B g_2^2 \sin^2 \theta_W \{ g_{\alpha\beta} p_2 \cdot p_4 - p_{2\beta} p_{4\alpha} \}]$$



$$\frac{-i}{4M_W^2} [(g_2 f_W \sin \theta_W - g_1 f_B \cos \theta_W)(g_1 \cos \theta_W + g_2 \sin \theta_W) \\ \{ p_{2\beta} p_{3\alpha} - p_3 \cdot p_2 g_{\alpha\beta} + p_{2\beta} p_{1\alpha} - p_2 \cdot p_1 g_{\alpha\beta} \} \\ - 16 d_B g_2^2 \cos \theta_W \sin \theta_W \{ g_{\alpha\beta} p_2 \cdot p_4 - p_{2\beta} p_{4\alpha} \}]$$



$$- \frac{4i d_B g_2^2 \cos^2 \theta_W}{M_W^2} \{ g_{\alpha\beta} p_2 \cdot p_4 - p_{2\beta} p_{4\alpha} \}$$

Appendix A : Helicity amplitudes for Boson-Boson fusion processes at High Energy due to $\mathcal{O}_{W\Phi}$ and $\mathcal{O}_{B\Phi}$ interactions

Below we give the amplitudes for the processes that do not vanish at high energies.

A.1 4- gauge boson processes

In general there are 81 helicity amplitudes $F_{\lambda\lambda'\mu\mu'}$ for each vector boson-vector boson fusion process $V_1(\lambda)V_2(\lambda') \rightarrow V_3(\mu)V_4(\mu')$. Taking into account parity conservation, (which is valid at tree level for the self-boson interactions contained in SM and the operators considered) we obtain

$$F_{\lambda\lambda'\mu\mu'}(\theta) = F_{-\lambda-\lambda'-\mu-\mu'}(\theta) (-1)^{\lambda-\lambda'-\mu+\mu'} , \quad (\text{A.1})$$

which reduces the number of independent amplitudes to 41. In specific channels this number is further reduced due to *e.g.* to the absence of helicity zero states for photons, the symmetrization for identical particles, charge conjugation relations, etc. Here and below θ is the c.m. angle between V_1 and V_3 . The normalization of the amplitudes is defined by noting that the differential cross section in c.m. is given by

$$\frac{d\sigma(\lambda\lambda'\mu\mu')}{d\cos\theta} = C |F_{\lambda\lambda'\mu\mu'}|^2 , \quad (\text{A.2})$$

where the coefficient

$$C = \frac{1}{32\pi s} \frac{p_{34}}{p_{12}} \quad (\text{A.3})$$

includes no spin average. This later choice is motivated by the fact that, inside the proton, different vector boson distribution functions occur for different initial helicity states. Finally p_{12} , p_{34} in (B.3) denote the c.m. momenta of the initial and final boson pairs respectively.

As in [8], for $s \gtrsim 1\text{TeV}^2$ simple and very accurate expressions for the $\mathcal{O}_{W\Phi}$ and $\mathcal{O}_{B\Phi}$ contributions to the boson amplitudes are obtained by neglecting terms of order $O(M_W^2/s)$ with respect to the leading ones. The independent amplitudes for the various processes are given below as coefficients of the specified products of coupling constants². The charge assignment of W is omitted whenever it is irrelevant.

²The terms linear in the coupling constants f_B and f_W coming from the diagrams which do not involve the Higgs boson have also been computed by I.Kuss [18].

$$\boxed{\gamma Z \rightarrow W^- W^+}$$

$$g_1^2 f_B^2$$

$$\begin{aligned} F_{+---} &= c_W F_{+0-0} = \frac{(\cos \theta - 1) c_W s_W s}{32 M_W^2} \\ F_{+-00} &= F_{++--} = -\frac{1}{2} F_{++00} = -\frac{c_W s_W s}{16 M_W^2} \\ F_{+--+} &= -c_W F_{+00-} = -\frac{(\cos \theta + 1) c_W s_W s}{32 M_W^2} \end{aligned} \quad (\text{A.4})$$

$$g_2^2 f_W^2$$

$$\begin{aligned} F_{+---} &= -\frac{s_W^2}{c_W} F_{+0-0} = \frac{(\cos \theta - 1) s_W^3 s}{32 c_W M_W^2} \\ F_{+-00} &= -\frac{1}{2} F_{++00} = \frac{s_W^2}{2} F_{++++} = -\frac{s_W^3 s}{16 c_W M_W^2} \\ F_{+--+} &= \frac{s_W^2}{c_W} F_{+00-} = -\frac{(\cos \theta + 1) s_W^3 s}{32 c_W M_W^2} \\ F_{++--} &= \frac{(c_W^2 - 3) s_W s}{16 c_W M_W^2} \end{aligned} \quad (\text{A.5})$$

$$e g_1 f_B$$

$$\begin{aligned} F_{+0-0} &= -\frac{(\cos \theta - 1) c_W s}{16 M_W^2 s_W} \\ F_{+00-} &= -\frac{(\cos \theta + 1) c_W s}{16 M_W^2 s_W} \quad F_{++00} = \frac{(3 - 4c_W^2) s}{8 M_W^2 s_W} \end{aligned} \quad (\text{A.6})$$

$$e g_2 f_W$$

$$\begin{aligned} F_{+0-0} &= -\frac{(\cos \theta - 1) s}{16 M_W^2} \quad F_{+00-} = -\frac{(\cos \theta + 1) s}{16 M_W^2} \\ F_{++00} &= \frac{(1 - 4c_W^2) s}{8 c_W M_W^2} \end{aligned} \quad (\text{A.7})$$

$g_1 f_B \ g_2 f_W$

$$\begin{aligned}
F_{+---} &= \frac{(\cos \theta - 1) s_W^2 s}{16M_W^2} & F_{+-00} &= -s_W^2 F_{++++} = -\frac{s_W^2 s}{8M_W^2} \\
F_{+--+} &= -\frac{(\cos \theta + 1) s_W^2 s}{16M_W^2} & F_{+0-0} &= \frac{(\cos \theta - 1) (1 - 2c_W^2) s}{32c_W M_W^2} \\
F_{+00-} &= \frac{(\cos \theta + 1) (1 - 2c_W^2) s}{32c_W M_W^2} & F_{++--} &= -\frac{1}{2} F_{++00} = \frac{c_W^2 s}{8M_W^2}
\end{aligned} \tag{A.8}$$

$$\boxed{\gamma W \rightarrow ZW}$$

$g_1^2 \ f_B^2$

$$\begin{aligned}
F_{+0+0} &= -F_{++--} = -\frac{1}{2} F_{+0-0} = \frac{(\cos \theta - 1) c_W s_W s}{32M_W^2} \\
F_{+00-} &= -\frac{1}{c_W} F_{+--+} = \frac{(\cos \theta + 1) s_W s}{32M_W^2} \\
F_{++++} &= -c_W F_{++00} = \frac{c_W s_W s}{16M_W^2}
\end{aligned} \tag{A.9}$$

$g_2^2 \ f_W^2$

$$\begin{aligned}
F_{+--+} &= \frac{s_W^2}{c_W} F_{+00-} = -\frac{(\cos \theta + 1) s_W^3 s}{32c_W M_W^2} \\
F_{+---} &= \frac{1}{s_W^2} F_{+0-0} = -\frac{2}{s_W^2} F_{+0+0} = -\frac{(\cos \theta - 1) s_W s}{16c_W M_W^2} \\
F_{++00} &= \frac{c_W^2}{s_W^2} F_{++++} = \frac{c_W s_W s}{16M_W^2} \\
F_{++--} &= \frac{(c_W^2 - 3)(\cos \theta - 1) s_W s}{32c_W M_W^2}
\end{aligned} \tag{A.10}$$

$e \ g_1 f_B$

$$\begin{aligned}
F_{++00} &= \frac{c_W s}{8M_W^2 s_W} & F_{+00-} &= -\frac{(\cos \theta + 1) c_W s}{16M_W^2 s_W} \\
F_{+0-0} &= -\frac{(\cos \theta - 1) (3 - 4c_W^2) s}{16M_W^2 s_W}
\end{aligned} \tag{A.11}$$

$e \ g_2 f_W$

$$\begin{aligned}
F_{++00} &= \frac{s}{8M_W^2} & F_{+00-} &= -\frac{(\cos \theta + 1) s}{16M_W^2} \\
F_{+0-0} &= -\frac{(\cos \theta - 1) (1 - 4c_W^2) s}{16M_W^2 c_W}
\end{aligned} \tag{A.12}$$

$g_1 f_B \ g_2 f_W$

$$\begin{aligned}
F_{+---+} &= \frac{1}{2c_W^2} F_{+0-0} = \frac{1}{s_W^2} F_{+0+0} \\
&= \frac{1}{c_W^2} F_{++--} = \frac{(\cos \theta - 1) s}{16M_W^2} \\
F_{+--+} &= -\frac{(\cos \theta + 1) s_W^2 s}{16M_W^2} \\
F_{+00-} &= \frac{(\cos \theta + 1) (1 - 2c_W^2) s}{32c_W M_W^2} \\
F_{++00} &= -\frac{(1 - 2c_W^2) s}{16c_W M_W^2} & F_{++++} &= \frac{s_W^2 s}{8M_W^2}
\end{aligned} \tag{A.13}$$

$$\boxed{\gamma\gamma \rightarrow W^- W^+}$$

$g_1^2 \ f_B^2$

$$F_{+---+} = -\frac{(\cos \theta - 1) c_W^2 s}{32M_W^2} \quad F_{+--+} = \frac{(\cos \theta + 1) c_W^2 s}{32M_W^2}$$

$$F_{+-00} = F_{++--} = -\frac{1}{2}F_{++00} = \frac{c_W^2 s}{16M_W^2} \quad (\text{A.14})$$

$$g_2^2 f_W^2$$

$$\begin{aligned} F_{+---} &= -\frac{(\cos \theta - 1) s_W^2 s}{32M_W^2} \\ F_{+-00} &= F_{++--} = -\frac{1}{2}F_{++00} = \frac{s_W^2 s}{16M_W^2} \\ F_{+--+} &= \frac{(\cos \theta + 1) s_W^2 s}{32M_W^2} \end{aligned} \quad (\text{A.15})$$

$$e g_1 f_B$$

$$F_{++00} = -\frac{c_W s}{2M_W^2} \quad (\text{A.16})$$

$$e g_2 f_W$$

$$F_{++00} = -\frac{s_W s}{2M_W^2} \quad (\text{A.17})$$

$$g_1 f_B g_2 f_W$$

$$\begin{aligned} F_{+---} &= -\frac{(\cos \theta - 1) c_W s_W s}{16M_W^2} & F_{+--+} &= \frac{(\cos \theta + 1) c_W s_W s}{16M_W^2} \\ F_{+-00} &= F_{++--} = -\frac{1}{2}F_{++00} = \frac{c_W s_W s}{8M_W^2} \end{aligned} \quad (\text{A.18})$$

$$\boxed{\gamma W \rightarrow \gamma W}$$

$$g_1^2 f_B^2$$

$$\begin{aligned} F_{+--+} &= \frac{(\cos \theta + 1) c_W^2 s}{32 M_W^2} & F_{++++} &= -\frac{c_W^2 s}{16 M_W^2} \\ F_{+0-0} &= -2F_{+0+0} = 2F_{++--} = \frac{(\cos \theta - 1) c_W^2 s}{16 M_W^2} \end{aligned} \quad (\text{A.19})$$

$$g_2^2 f_W^2$$

$$\begin{aligned} F_{+--+} &= \frac{(\cos \theta + 1) s_W^2 s}{32 M_W^2} & F_{++++} &= -\frac{s_W^2 s}{16 M_W^2} \\ F_{+0-0} &= -2F_{+0+0} = 2F_{++--} = \frac{(\cos \theta - 1) s_W^2 s}{16 M_W^2} \end{aligned} \quad (\text{A.20})$$

$$e g_1 f_B$$

$$F_{+0-0} = \frac{(\cos \theta - 1) c_W s}{4 M_W^2} \quad (\text{A.21})$$

$$e g_2 f_W$$

$$F_{+0-0} = \frac{(\cos \theta - 1) s_W s}{4 M_W^2} \quad (\text{A.22})$$

$$g_1 f_B g_2 f_W$$

$$\begin{aligned} F_{+--+} &= \frac{(\cos \theta + 1) c_W s_W s}{16 M_W^2} & F_{++++} &= -\frac{c_W s_W s}{8 M_W^2} \\ F_{+0-0} &= -2F_{+0+0} = 2F_{++--} = \frac{(\cos \theta - 1) c_W s_W s}{8 M_W^2} \end{aligned} \quad (\text{A.23})$$

$$\boxed{\gamma\gamma \rightarrow ZZ}$$

$$g_1^2 f_B^2$$

$$\begin{aligned} F_{+---} &= -\frac{(\cos\theta - 1)s}{32M_W^2} & F_{+--+} &= \frac{(\cos\theta + 1)s}{32M_W^2} \\ F_{++--} &= \frac{s}{16M_W^2} \end{aligned} \quad (\text{A.24})$$

$$g_2^2 f_W^2$$

$$\begin{aligned} F_{+---} &= -\frac{(\cos\theta - 1)s_W^2 s}{32c_W^2 M_W^2} & F_{+--+} &= \frac{(\cos\theta + 1)s_W^2 s}{32c_W^2 M_W^2} \\ F_{++--} &= \frac{s_W^2 s}{16c_W^2 M_W^2} \end{aligned} \quad (\text{A.25})$$

$$g_1 f_B g_2 f_W$$

$$\begin{aligned} F_{+---} &= \frac{(\cos\theta - 1)s_W s}{16c_W M_W^2} & F_{+--+} &= -\frac{(\cos\theta + 1)s_W s}{16c_W M_W^2} \\ F_{++--} &= -\frac{s_W s}{8c_W M_W^2} \end{aligned} \quad (\text{A.26})$$

$$\boxed{\gamma Z \rightarrow \gamma Z}$$

$$g_1^2 f_B^2$$

$$\begin{aligned} F_{++--} &= \frac{(\cos\theta - 1)s}{32M_W^2} & F_{+--+} &= \frac{(\cos\theta + 1)s}{32M_W^2} \\ F_{++++} &= -\frac{s}{16M_W^2} \end{aligned} \quad (\text{A.27})$$

$$g_2^2 f_W^2$$

$$F_{++--} = \frac{(\cos\theta - 1)s_W^2 s}{32c_W^2 M_W^2} \quad F_{+--+} = \frac{(\cos\theta + 1)s_W^2 s}{32c_W^2 M_W^2}$$

$$F_{++++} = -\frac{s_W^2 s}{16c_W^2 M_W^2} \quad (\text{A.28})$$

$g_1 f_B \ g_2 f_W$

$$\begin{aligned} F_{++--} &= -\frac{(\cos \theta - 1) s_W s}{16c_W M_W^2} & F_{+-+-} &= -\frac{(\cos \theta + 1) s_W s}{16c_W M_W^2} \\ F_{++++} &= \frac{s_W s}{8c_W M_W^2} \end{aligned} \quad (\text{A.29})$$

$$\boxed{\gamma Z \rightarrow Z Z}$$

$g_1^2 \ f_B^2$

$$\begin{aligned} F_{+--+} &= -F_{+00-} = -\frac{(\cos \theta + 1) s_W s}{16c_W M_W^2} & F_{++++} &= -F_{++00} = \frac{s_W s}{8c_W M_W^2} \\ F_{+--+} &= F_{+0-0} = \frac{(\cos \theta - 1) s_W s}{16c_W M_W^2} \end{aligned} \quad (\text{A.30})$$

$g_2^2 \ f_W^2$

$$\begin{aligned} F_{+--+} &= F_{+0-0} = -\frac{(\cos \theta - 1) s_W s}{16c_W M_W^2} & F_{+-+-} &= -F_{+00-} = \frac{(\cos \theta + 1) s_W s}{16c_W M_W^2} \\ F_{++00} &= -F_{++++} = \frac{s_W s}{8c_W M_W^2} \end{aligned} \quad (\text{A.31})$$

$e \ g_1 f_B$

$$\begin{aligned} F_{+0-0} &= -\frac{(\cos \theta - 1) s}{16s_W M_W^2} & F_{+00-} &= -\frac{(\cos \theta + 1) s}{16s_W M_W^2} \\ F_{++00} &= \frac{s}{8s_W M_W^2} \end{aligned} \quad (\text{A.32})$$

$e \ g_2 f_W$

$$\begin{aligned}
F_{+0-0} &= \frac{(\cos \theta - 1) s}{16c_W M_W^2} & F_{+00-} &= \frac{(\cos \theta + 1) s}{16c_W M_W^2} \\
F_{++00} &= -\frac{s}{8c_W M_W^2}
\end{aligned} \tag{A.33}$$

$g_1 f_B \ g_2 f_W$

$$\begin{aligned}
F_{+--+} &= F_{+0-0} = -\frac{(\cos \theta - 1) (1 - 2c_W^2) s}{16c_W^2 M_W^2} \\
F_{+-+-} &= -F_{+00-} = \frac{(\cos \theta + 1) (1 - 2c_W^2) s}{16c_W^2 M_W^2} \\
F_{++00} &= -F_{++++} = \frac{(1 - 2c_W^2) s}{8c_W^2 M_W^2}
\end{aligned} \tag{A.34}$$

$$\boxed{ZZ \rightarrow ZZ}$$

$g_1^2 \ f_B^2$

$$\begin{aligned}
F_{00++} &= F_{++00} = -F_{++++} = \frac{s_W^2 s}{4c_W^2 M_W^2} \\
F_{0+-0} &= -F_{+-+-} = F_{+00-} = -\frac{(\cos \theta + 1) s_W^2 s}{8c_W^2 M_W^2} \\
F_{0+0-} &= F_{+--+} = F_{+0-0} = -\frac{(\cos \theta - 1) s_W^2 s}{8c_W^2 M_W^2}
\end{aligned} \tag{A.35}$$

$g_2^2 \ f_W^2$

$$F_{00++} = F_{++00} = -F_{++++} = \frac{s}{4M_W^2}$$

$$\begin{aligned}
F_{0+-0} &= -F_{+--+} = F_{+00-} = -\frac{(\cos \theta + 1) s}{8M_W^2} \\
F_{0+0-} &= F_{+--+} = F_{+0-0} = -\frac{(\cos \theta - 1) s}{8M_W^2}
\end{aligned} \tag{A.36}$$

$e \ g_1 f_B$

$$\begin{aligned}
F_{00++} &= F_{++00} = -\frac{s}{4c_W M_W^2} & F_{0+-0} &= F_{+00-} = \frac{(\cos \theta + 1) s}{8c_W M_W^2} \\
F_{0+0-} &= F_{+0-0} = \frac{(\cos \theta - 1) s}{8c_W M_W^2}
\end{aligned} \tag{A.37}$$

$e \ g_2 f_W$

$$\begin{aligned}
F_{00++} &= F_{++00} = -\frac{s}{4s_W M_W^2} & F_{0+-0} &= F_{+00-} = \frac{(\cos \theta + 1) s}{8s_W M_W^2} \\
F_{0+0-} &= F_{+0-0} = \frac{(\cos \theta - 1) s}{8s_W M_W^2}
\end{aligned} \tag{A.38}$$

$g_1 f_B \ g_2 f_W$

$$\begin{aligned}
F_{00++} &= F_{++00} = -F_{++++} = \frac{s_W s}{2c_W M_W^2} \\
F_{0+-0} &= -F_{+--+} = F_{+00-} = -\frac{(\cos \theta + 1) s_W s}{4c_W M_W^2} \\
F_{0+0-} &= F_{+--+} = F_{+0-0} = -\frac{(\cos \theta - 1) s_W s}{4c_W M_W^2}
\end{aligned} \tag{A.39}$$

$$\boxed{W^- W^+ \rightarrow Z Z}$$

$$g_1^2 f_B^2$$

$$\begin{aligned} c_W^2 F_{0000} &= F_{++--} = F_{00+-} = -\frac{1}{2} F_{00++} = \frac{s_W^2 s}{16 M_W^2} \\ c_W F_{0+-0} &= -F_{+-+-} = c_W F_{+00-} = -\frac{(\cos \theta + 1) s_W^2 s}{32 M_W^2} \\ c_W F_{0+0-} &= F_{+---} = c_W F_{+0-0} = -\frac{(\cos \theta - 1) s_W^2 s}{32 M_W^2} \end{aligned} \quad (\text{A.40})$$

$$g_2^2 f_W^2$$

$$F_{0000} = \frac{(3 - \cos^2 \theta) s^2}{32 M_W^4} \quad (\text{A.41})$$

$$e g_1 f_B$$

$$\begin{aligned} F_{+0-0} &= F_{0+0-} = \frac{(\cos \theta - 1) s}{16 M_W^2} & F_{+00-} &= F_{0+-0} = \frac{(\cos \theta + 1) s}{16 M_W^2} \\ F_{00++} &= \frac{(2c_W^2 - 1) s}{4c_W M_W^2} \end{aligned} \quad (\text{A.42})$$

$$e g_2 f_W$$

$$\begin{aligned} F_{++00} &= \frac{1}{2c_W^2 - 1} F_{00++} = -\frac{1}{3} F_{0000} = -\frac{s}{4s_W M_W^2} \\ F_{+0-0} &= F_{0+0-} = \frac{(\cos \theta - 1) s_W s}{16c_W M_W^2} \\ F_{+00-} &= F_{0+-0} = \frac{(\cos \theta + 1) s_W s}{16c_W M_W^2} \end{aligned} \quad (\text{A.43})$$

$$g_1 f_B g_2 f_W$$

$$F_{++00} = -F_{++++} = \frac{2}{s_W^2} F_{00+-} = -\frac{2}{3} F_{0000} = \frac{s_W s}{4c_W M_W^2}$$

$$\begin{aligned}
F_{00++} &= -2F_{++--} = \frac{(1 + c_W^2) s_W s}{4c_W M_W^2} \\
F_{0+-0} &= F_{+00-} = \frac{(\cos \theta + 1) (2c_W^2 - 1) s_W s}{32c_W^2 M_W^2} \\
F_{0+0-} &= F_{+0-0} = \frac{(\cos \theta - 1) (2c_W^2 - 1) s_W s}{32c_W^2 M_W^2} \\
F_{+---+} &= -\frac{(\cos \theta - 1) s_W^3 s}{16c_W M_W^2} \quad F_{+--+} = \frac{(\cos \theta + 1) s_W^3 s}{16c_W M_W^2}
\end{aligned} \tag{A.44}$$

$$\boxed{ZW \rightarrow ZW}$$

$$g_1^2 f_B^2$$

$$\begin{aligned}
F_{0000} &= \frac{(\cos \theta - 1) s_W^2 s}{32c_W^2 M_W^2} \\
F_{00++} &= F_{++00} = \frac{s_W^2 s}{16c_W M_W^2} \\
F_{+00-} &= F_{0+-0} = -\frac{(\cos \theta + 1) s_W^2 s}{32c_W M_W^2} \\
F_{+0-0} &= -2F_{+0+0} = 2c_W F_{++--} = \frac{(\cos \theta - 1) s_W^2 s}{16M_W^2} \\
F_{-++-} &= \frac{(\cos \theta + 1) s_W^2 s}{32M_W^2} \quad F_{++++} = -\frac{s_W^2 s}{16M_W^2}
\end{aligned} \tag{A.45}$$

$$g_2^2 f_W^2$$

$$F_{0000} = \frac{(\cos^2 \theta - 6 \cos \theta - 3) s^2}{64M_W^4} \tag{A.46}$$

$$e g_1 f_B$$

$$F_{00++} = F_{++00} = -\frac{s}{8M_W^2} \quad F_{0+-0} = F_{+00-} = \frac{(\cos \theta + 1) s}{16M_W^2}$$

$$F_{+0-0} = -\frac{(2c_W^2 - 1) (\cos \theta - 1) s}{8c_W M_W^2} \quad (\text{A.47})$$

$e \ g_2 f_W$

$$\begin{aligned} F_{0000} &= 3F_{0+0-} = \frac{3(\cos \theta - 1) s}{8s_W M_W^2} & F_{00++} &= F_{++00} = -\frac{s_W s}{8c_W M_W^2} \\ F_{+00-} &= F_{0+-0} = \frac{(\cos \theta + 1) s_W s}{16c_W M_W^2} & F_{+0-0} &= \frac{(\cos \theta - 1) (2c_W^2 - 1) s}{8s_W M_W^2} \end{aligned} \quad (\text{A.48})$$

$g_1 f_B \ g_2 f_W$

$$\begin{aligned} F_{0000} &= \frac{3}{2}F_{-++-} = \frac{3}{s_W^2}F_{+0+0} = \frac{3}{2}F_{0+0-} = -\frac{3(\cos \theta - 1) s_W s}{16c_W M_W^2} \\ F_{00++} &= F_{++00} = \frac{(1 - 2c_W^2) s_W s}{16c_W^2 M_W^2} \\ F_{0+-0} &= F_{+00-} = \frac{(\cos \theta + 1) (2c_W^2 - 1) s_W s}{32c_W^2 M_W^2} \\ F_{+0-0} &= 2F_{++--} = -\frac{(\cos \theta - 1) (c_W^2 + 1) s_W s}{8c_W M_W^2} \\ F_{-++-} &= \frac{(\cos \theta + 1) s_W^3 s}{16c_W M_W^2} & F_{++++} &= -\frac{s_W^3 s}{8c_W M_W^2} \end{aligned} \quad (\text{A.49})$$

$$\boxed{W^- W^+ \rightarrow W^- W^+}$$

$g_1^2 \ f_B^2$

$$F_{0000} = \frac{(3 - 6 \cos \theta - \cos^2 \theta) s^2}{64M_W^4} \quad (\text{A.50})$$

$g_2^2 \ f_W^2$

$$F_{0000} = \frac{(3 - 6 \cos \theta - \cos^2 \theta) s^2}{64M_W^4} \quad (\text{A.51})$$

$$e \ g_1 f_B \quad F_{0000} = \frac{3(1 + \cos \theta) \ s}{8c_W M_W^2} \quad (\text{A.52})$$

$$e \ g_2 f_W \quad \begin{aligned} F_{0000} &= \frac{3(1 + \cos \theta) \ s}{8s_W M_W^2} & F_{00++} &= -\frac{s}{4s_W M_W^2} \\ F_{0+0-} &= F_{+0-0} = \frac{(\cos \theta - 1) \ s}{8s_W M_W^2} \end{aligned} \quad (\text{A.53})$$

$$g_1 f_B \ g_2 f_W \quad \begin{aligned} F_{0000} &= F_{00+-} = -F_{0+0+} = F_{+00+} = \\ &= F_{0++0} = F_{+-00} = -F_{+0+0} = \frac{(\cos \theta + 1) \ s_W \ s}{16c_W M_W^2} \end{aligned} \quad (\text{A.54})$$

$$g_1^2 \ f_B^2 \quad \boxed{W^+ W^+ \rightarrow W^+ W^+} \quad F_{0000} = \frac{(\cos^2 \theta - 3) \ s^2}{32M_W^4} \quad (\text{A.55})$$

$$g_2^2 \ f_W^2 \quad F_{0000} = \frac{(\cos^2 \theta - 3) \ s^2}{32M_W^4} \quad (\text{A.56})$$

$$e \ g_1 f_B \quad F_{0000} = -\frac{3s}{4c_W M_W^2} \quad (\text{A.57})$$

$e \ g_2 f_W$

$$\begin{aligned}
F_{0000} &= -\frac{3s}{4s_W M_W^2} & F_{+00-} = F_{0+-0} &= \frac{(\cos \theta + 1) s}{8s_W M_W^2} \\
F_{0+0-} &= F_{+0-0} = \frac{(\cos \theta - 1) s}{8s_W M_W^2}
\end{aligned} \tag{A.58}$$

$g_1 f_B \ g_2 f_W$

$$\begin{aligned}
F_{0000} &= F_{00+-} = F_{0++0} = F_{+-00} = \\
&= F_{+00+} = -F_{0+0+} = -F_{+0+0} = -\frac{s_W s}{8c_W M_W^2}
\end{aligned} \tag{A.59}$$

A.2 Single Higgs processes

There are three helicity indices in the amplitudes now, and the constrain from parity conservation in the bosonic sector is given by a relation analogous to (A.1) with the Higgs treated as longitudinal vector boson.

$$\begin{aligned}
&\boxed{W^- W^+ \rightarrow H Z} \\
g_1^2 \ f_B^2 & \\
F_{000} &= \frac{\cos \theta \ s^2}{16M_W^4}
\end{aligned} \tag{A.60}$$

$$\begin{aligned}
g_2^2 \ f_W^2 & \\
-F_{\pm 00} &= -F_{0\mp 0} = \frac{F_{00\mp}}{c_W} = \pm \frac{\sin \theta \ s \sqrt{s}}{16\sqrt{2}M_W^3}
\end{aligned} \tag{A.61}$$

$e \ g_1 f_B$

$$\begin{aligned}
F_{\pm 0 \mp} &= \frac{(\cos \theta + 1) \ s}{16 M_W^2} \\
F_{0 \mp \pm} &= -\frac{(\cos \theta - 1) \ s}{16 M_W^2} \\
F_{000} &= -\frac{\cos \theta \ s}{4 c_W M_W^2}
\end{aligned} \tag{A.62}$$

$e \ g_2 f_W$

$$\begin{aligned}
F_{\mp 0 \pm} &= \frac{(\cos \theta + 1) \ s_W \ s}{16 c_W M_W^2} \\
F_{0 \mp \pm} &= -\frac{(\cos \theta - 1) \ s_W \ s}{16 c_W M_W^2}
\end{aligned} \tag{A.63}$$

$g_1 f_B \ g_2 f_W$

$$-F_{\pm 00} = -F_{0 \mp 0} = \frac{F_{00\pm}}{2 c_W} = \pm \frac{\sin \theta \ s_W \ s \sqrt{s}}{16 \sqrt{2} c_W M_W^3} \tag{A.64}$$

$g_1^2 \ f_B^2$

$$\boxed{ZW \rightarrow HW}$$

$$F_{000} = -\frac{(\cos^2 \theta + 2 \cos \theta - 3) \ s^2}{64 M_W^4} \tag{A.65}$$

$g_2^2 \ f_W^2$

$$F_{0 \mp 0} = \frac{1}{c_W} F_{\pm 00} = F_{00\pm} = \pm \frac{\sin \theta \ s \sqrt{s}}{16 \sqrt{2} M_W^3} \tag{A.66}$$

$e \ g_1 f_B$

$$\begin{aligned}
F_{\pm\pm 0} &= -\frac{s}{8M_W^2} \\
F_{\pm 0\mp} &= -\frac{(\cos\theta + 1) s}{16M_W^2} \\
F_{000} &= \frac{(3 + \cos\theta) s}{8c_W M_W^2}
\end{aligned} \tag{A.67}$$

$e \ g_2 f_W$

$$F_{\pm\pm 0} = -\frac{s_W s}{8c_W M_W^2} \quad F_{\pm 0\mp} = -\frac{(\cos\theta + 1) s_W s}{16c_W M_W^2} \tag{A.68}$$

$g_1 f_B \ g_2 f_W$

$$F_{0\mp 0} = \frac{F_{\mp 00}}{2c_W} = F_{00\pm} = \pm \frac{\sin\theta \ s_W \ s\sqrt{s}}{16\sqrt{2}c_W M_W^3} \tag{A.69}$$

$g_1^2 \ f_B^2$

$$\boxed{H\gamma \rightarrow W^- W^+}$$

$$F_{\pm 00} = \mp \frac{\sin\theta \ s_W \ s\sqrt{s}}{16\sqrt{2}M_W^3} \tag{A.70}$$

$g_2^2 \ f_W^2$

$$F_{\pm 00} = \pm \frac{\sin\theta \ s_W \ s\sqrt{s}}{16\sqrt{2}M_W^3} \tag{A.71}$$

$e \ g_1 f_B$

$$F_{\pm\mp 0} = -\frac{(\cos\theta + 1) c_W s}{16s_W M_W^2} \quad F_{\pm 0\mp} = \frac{(\cos\theta - 1) c_W s}{16s_W M_W^2} \tag{A.72}$$

$$e \ g_2 f_W \quad F_{\pm\mp 0} = -\frac{(\cos\theta + 1) \ s}{16M_W^2} \quad F_{\pm 0\mp} = \frac{(\cos\theta - 1) \ s}{16M_W^2} \quad (\text{A.73})$$

$$g_1 f_B \ g_2 f_W \quad F_{\pm 00} = \pm \frac{\sin\theta \ (1 + 2c_W^2) \ s\sqrt{s}}{16\sqrt{2}c_W M_W^3} \quad (\text{A.74})$$

$$g_1^2 \ f_B^2 \quad \boxed{\gamma W \rightarrow HW} \quad F_{\pm 00} = \mp \frac{\sin\theta \ s_W \ s\sqrt{s}}{16\sqrt{2}M_W^3} \quad (\text{A.75})$$

$$g_2^2 \ f_W^2 \quad F_{\pm 00} = \pm \frac{\sin\theta \ s_W \ s\sqrt{s}}{16\sqrt{2}M_W^3} \quad (\text{A.76})$$

$$e \ g_1 f_B \quad F_{\pm 0\mp} = \frac{(\cos\theta + 1) \ c_W \ s}{16s_W M_W^2} \quad F_{\pm\pm 0} = \frac{c_W \ s}{8s_W M_W^2} \quad (\text{A.77})$$

$$e \ g_2 f_W \quad F_{\pm 0\mp} = \frac{(\cos\theta + 1) \ s}{16M_W^2} \quad F_{\pm\pm 0} = \frac{s}{8M_W^2} \quad (\text{A.78})$$

$$g_1 f_B \ g_2 f_W \quad F_{\pm 00} = \pm \frac{\sin\theta \ (1 + 2c_W^2) \ s\sqrt{s}}{16\sqrt{2}c_W M_W^3} \quad (\text{A.79})$$

A.3 Two Higgs processes

$$\begin{array}{c}
\boxed{HZ \rightarrow HZ} \\
g_1^2 f_B^2 \\
F_{00} = \frac{(\cos^2 \theta - 6 \cos \theta - 3) s^2}{64 M_W^4}
\end{array} \tag{A.80}$$

$$\begin{array}{c}
g_2^2 f_W^2 \\
F_{00} = \frac{(\cos^2 \theta - 6 \cos \theta - 3) s^2}{64 M_W^4}
\end{array} \tag{A.81}$$

$$\begin{array}{c}
e g_1 f_B \\
F_{+-} = \frac{1}{3} F_{00} = \frac{(\cos \theta - 1) s}{8 c_W M_W^2}
\end{array} \tag{A.82}$$

$$\begin{array}{c}
e g_2 f_W \\
F_{+-} = \frac{1}{3} F_{00} = \frac{(\cos \theta - 1) s}{8 s_W M_W^2}
\end{array} \tag{A.83}$$

$$\begin{array}{c}
g_1 f_B g_2 f_W \\
F_{00} = -2 F_{-+} = \frac{4}{3} F_{++} = -\frac{(\cos \theta - 1) s_W s}{4 c_W M_W^2}
\end{array} \tag{A.84}$$

$$\begin{array}{c}
\boxed{ZZ \rightarrow HH} \\
g_1^2 f_B^2 \\
F_{00} = \frac{(3 - \cos^2 \theta) s^2}{32 M_W^4}
\end{array} \tag{A.85}$$

$$g_2^2 f_W^2 \quad F_{00} = \frac{(3 - \cos^2 \theta) s^2}{32 M_W^4} \quad (\text{A.86})$$

$$e g_1 f_B \quad F_{--} = -\frac{1}{3} F_{00} = -\frac{s}{4 c_W M_W^2} \quad (\text{A.87})$$

$$e g_2 f_W \quad F_{--} = -\frac{1}{3} F_{00} = -\frac{s}{4 s_W M_W^2} \quad (\text{A.88})$$

$$g_1 f_B g_2 f_W \quad F_{00} = 2 F_{++} = -\frac{4}{3} F_{-+} = -\frac{s_W s}{2 c_W M_W^2} \quad (\text{A.89})$$

$$g_1^2 f_B^2 \quad \boxed{H \gamma \rightarrow H Z} \quad F_{-\mp} = \pm \frac{(\cos \theta - 1) s_W s}{16 c_W M_W^2} \quad (\text{A.90})$$

$$g_2^2 f_W^2 \quad F_{-\pm} = \pm \frac{(\cos \theta - 1) s_W s}{16 c_W M_W^2} \quad (\text{A.91})$$

$$e g_1 f_B \quad F_{-+} = -\frac{(\cos \theta - 1) s}{16 s_W M_W^2} \quad (\text{A.92})$$

$$e \ g_2 f_W$$

$$F_{-+} = \frac{(\cos \theta - 1) s}{16 c_W M_W^2} \quad (\text{A.93})$$

$$g_1 f_B \ g_2 f_W$$

$$F_{-\mp} = \pm \frac{(\cos \theta - 1) (2 c_W^2 - 1) s}{16 c_W^2 M_W^2} \quad (\text{A.94})$$

$$g_1^2 \ f_B^2$$

$$\boxed{\gamma Z \rightarrow H H} \quad F_{-\mp} = \pm \frac{s_W s}{8 c_W M_W^2} \quad (\text{A.95})$$

$$g_2^2 \ f_W^2$$

$$F_{-\pm} = \pm \frac{s_W s}{8 c_W M_W^2} \quad (\text{A.96})$$

$$e \ g_1 f_B$$

$$F_{--} = \frac{s}{8 s_W M_W^2} \quad (\text{A.97})$$

$$e \ g_2 f_W$$

$$F_{--} = -\frac{s}{8 c_W M_W^2} \quad (\text{A.98})$$

$$g_1 f_B \ g_2 f_W$$

$$F_{-\mp} = \pm \frac{(2 c_W^2 - 1) s}{8 c_W^2 M_W^2} \quad (\text{A.99})$$

$$\begin{array}{c}
\boxed{H\gamma \rightarrow H\gamma} \\
g_1^2 f_B^2
\end{array}
\quad
F_{--} = -\frac{1}{2}F_{-+} = -\frac{(\cos\theta - 1) s}{32M_W^2}
\quad (\text{A.100})$$

$$\begin{array}{c}
g_2^2 f_W^2
\end{array}
\quad
F_{--} = -\frac{1}{2}F_{-+} = -\frac{(\cos\theta - 1) s_W^2 s}{32c_W^2 M_W^2}
\quad (\text{A.101})$$

$$\begin{array}{c}
g_1 f_B g_2 f_W
\end{array}
\quad
F_{--} = -\frac{1}{2}F_{-+} = \frac{(\cos\theta - 1) s_W s}{16c_W M_W^2}
\quad (\text{A.102})$$

$$\begin{array}{c}
\boxed{\gamma\gamma \rightarrow HH} \\
g_1^2 f_B^2
\end{array}
\quad
F_{--} = -2F_{-+} = -\frac{s}{8M_W^2}
\quad (\text{A.103})$$

$$\begin{array}{c}
g_2^2 f_W^2
\end{array}
\quad
F_{--} = -2F_{-+} = -\frac{s_W^2 s}{8c_W^2 M_W^2}
\quad (\text{A.104})$$

$$\begin{array}{c}
g_1 f_B g_2 f_W
\end{array}
\quad
F_{--} = -2F_{-+} = \frac{s_W s}{4c_W M_W^2}
\quad (\text{A.105})$$

$$\begin{array}{c}
\boxed{HW \rightarrow HW} \\
g_2^2 \ f_W^2 \\
F_{00} = -\frac{(3 + 2 \cos \theta - \cos^2 \theta) \ s^2}{64 \ M_W^4}
\end{array} \tag{A.106}$$

$$\begin{array}{c}
e \ g_2 f_W \\
F_{-+} = \frac{F_{00}}{3} = \frac{(\cos \theta - 1) \ s}{8 M_W^2 s_W}
\end{array} \tag{A.107}$$

$$\begin{array}{c}
\boxed{W^- W^+ \rightarrow HH} \\
g_2^2 \ f_W^2 \\
F_{00} = \frac{(3 - \cos^2 \theta) \ s^2}{32 M_W^4}
\end{array} \tag{A.108}$$

$$\begin{array}{c}
e \ g_2 f_W \\
F_{++} = -\frac{F_{00}}{3} = -\frac{s}{4 M_W^2 s_W}
\end{array} \tag{A.109}$$

Appendix B : Helicity amplitudes for Boson-Boson fusion processes at High Energy due to the \mathcal{O}_{UB} interaction

The non vanishing processes at high energies are determined by the following amplitudes.

B.1 4-gauge boson processes

In analogy to the \mathcal{O}_{UW} treatment in [8], it is convenient to express the \mathcal{O}_{UB} contribution to the helicity amplitudes at $s \gtrsim 1TeV^2$, as functions of the initial and final helicities. Below we give the vector boson fusion amplitudes for the processes

$$V_1(\lambda) V_2(\lambda') \rightarrow V_3(\mu) V_4(\mu') \quad , \quad (B.1)$$

where the helicities are indicated in parentheses. The masses of the vector bosons are denoted by m_j for $(j = 1, \dots, 4)$, while ϵ_1, ϵ_2 denote the polarization vectors for the initial boson states, and ϵ_3, ϵ_4 the complex conjugate ones for the final states. Finally θ is the c.m. scattering angle; ($z \equiv \cos\theta$). For $s \gtrsim 1TeV^2$ we have

$$\begin{aligned} (\epsilon_1 \epsilon_2) &= -\frac{s}{2m_1 m_2} (1 - \lambda^2)(1 - \lambda'^2) \\ (\epsilon_1 \epsilon_3) &= \frac{s(1 - \cos\theta)}{4m_1 m_3} (1 - \mu^2)(1 - \lambda^2) \\ (\epsilon_1 \epsilon_4) &= -\frac{s(1 + \cos\theta)}{4m_1 m_4} (1 - \mu'^2)(1 - \lambda^2) \\ (\epsilon_2 \epsilon_3) &= -\frac{s(1 + \cos\theta)}{4m_2 m_3} (1 - \mu^2)(1 - \lambda'^2) \\ (\epsilon_2 \epsilon_4) &= \frac{s(1 - \cos\theta)}{4m_2 m_4} (1 - \mu'^2)(1 - \lambda'^2) \\ (\epsilon_3 \epsilon_4) &= -\frac{s}{2m_3 m_4} (1 - \mu^2)(1 - \mu'^2) \quad , \end{aligned} \quad (B.2)$$

and the definitions

$$\begin{aligned} V_{12} &= \frac{s}{4} \lambda^2 \lambda'^2 (1 + \lambda \lambda') \quad ; \quad V_{34} = \frac{s}{4} \mu^2 \mu'^2 (1 + \mu \mu') \\ V_{13} &= \frac{s}{8} (1 - \lambda \mu) (1 - \cos\theta) \mu^2 \lambda^2 \quad ; \quad V_{24} = \frac{s}{8} (1 - \lambda' \mu') (1 - \cos\theta) \mu'^2 \lambda'^2 \\ V_{14} &= \frac{s}{8} (1 - \lambda \mu') (1 + \cos\theta) \mu'^2 \lambda^2 \quad ; \quad V_{23} = \frac{s}{8} (1 - \lambda' \mu) (1 + \cos\theta) \mu^2 \lambda'^2 \end{aligned} \quad (B.3)$$

$$Z_{ij}^B = (\epsilon_i \epsilon_j) \frac{M_W}{c_W^2} - \frac{2d_B}{M_W} s_W^2 V_{ij} \quad (B.4)$$

The Higgs propagator is written as

$$D_H(x) \equiv x - \mathcal{M}_H^2 \quad (\text{B.5})$$

where $\mathcal{M}_H^2 \equiv M_H^2$ for $x = t$ or u , and $\mathcal{M}_H^2 \equiv M_H^2 - i M_H \Gamma_H$ when $x = s$.

We find

$$F_H(\gamma W \rightarrow \gamma W) = 2g_2^2 c_W^2 d_B V_{13}(\epsilon_2 \epsilon_4) \frac{1}{D_H(t)} \quad (\text{B.6})$$

$$F_H(\gamma W \rightarrow ZW) = -\frac{s_W}{c_W} F_H(\gamma W \rightarrow \gamma W) \quad (\text{B.7})$$

$$F_H(ZW \rightarrow \gamma W) = F_H(\gamma W \rightarrow ZW) \quad (\text{B.8})$$

$$F_H(ZW \rightarrow ZW) = -g_2^2 Z_{13}^B(\epsilon_2 \epsilon_4) M_W \frac{1}{D_H(t)} \quad (\text{B.9})$$

$$F_H(\gamma\gamma \rightarrow WW) = 2g_2^2 c_W^2 d_B V_{12}(\epsilon_3 \epsilon_4) \frac{1}{D_H(s)} \quad (\text{B.10})$$

$$F_H(\gamma Z \rightarrow WW) = -\frac{s_W}{c_W} F_H(\gamma\gamma \rightarrow WW) \quad (\text{B.11})$$

$$F_H(ZZ \rightarrow WW) = -g_2^2 Z_{12}^B(\epsilon_3 \epsilon_4) M_W \frac{1}{D_H(s)} \quad (\text{B.12})$$

$$F_H(ZZ \rightarrow ZZ) = -g_2^2 \left\{ Z_{12}^B Z_{34}^B \frac{1}{D_H(s)} + Z_{13}^B Z_{24}^B \frac{1}{D_H(t)} + Z_{14}^B Z_{23}^B \frac{1}{D_H(u)} \right\} \quad (\text{B.13})$$

$$F_H(W^+ W^- \rightarrow \gamma\gamma) = 2g_2^2 c_W^2 d_B V_{34}(\epsilon_1 \epsilon_2) \frac{1}{D_H(s)} \quad (\text{B.14})$$

$$F_H(W^+ W^- \rightarrow \gamma Z) = -\frac{s_W}{c_W} F_H(W^+ W^- \rightarrow \gamma\gamma) \quad (\text{B.15})$$

$$F_H(W^+ W^- \rightarrow ZZ) = -g_2^2(\epsilon_1 \epsilon_2) Z_{34}^B M_W \frac{1}{D_H(s)} \quad (\text{B.16})$$

$$F_H(\gamma\gamma \rightarrow \gamma\gamma) = -\frac{4g_2^2 c_W^4 d_B^2}{M_W^2} \left\{ \frac{V_{12} V_{34}}{D_H(s)} + \frac{V_{13} V_{24}}{D_H(t)} + \frac{V_{14} V_{23}}{D_H(u)} \right\} \quad (\text{B.17})$$

$$F_H(\gamma Z \rightarrow \gamma\gamma) = -\frac{s_W}{c_W} F_H(\gamma\gamma \rightarrow \gamma\gamma) \quad (\text{B.18})$$

$$F_H(ZZ \rightarrow \gamma\gamma) = g_2^2 \left\{ \frac{2c_W^2 d_B}{M_W} \frac{Z_{12}^B V_{34}}{D_H(s)} - \frac{4s_W^2 c_W^2 d_B^2}{M_W^2} \left[\frac{V_{13} V_{24}}{D_H(t)} + \frac{V_{14} V_{23}}{D_H(u)} \right] \right\} \quad (\text{B.19})$$

$$F_H(\gamma\gamma \rightarrow \gamma Z) = -\frac{s_W}{c_W} F_H(\gamma\gamma \rightarrow \gamma\gamma) \quad (\text{B.20})$$

$$F_H(\gamma Z \rightarrow \gamma Z) = g_2^2 \left\{ \frac{2c_W^2 d_B Z_{24}^B V_{13}}{M_W D_H(t)} - \frac{4c_W^2 s_W^2 d_B^2}{M_W^2} \left[\frac{V_{12} V_{34}}{D_H(s)} + \frac{V_{14} V_{23}}{D_H(u)} \right] \right\} \quad (\text{B.21})$$

$$F_H(ZZ \rightarrow \gamma Z) = -2g_2^2 \frac{s_W c_W d_B}{M_W} \left\{ \frac{Z_{12}^B V_{34}}{D_H(s)} + \frac{V_{13} Z_{24}^B}{D_H(t)} + \frac{Z_{14}^B V_{23}}{D_H(u)} \right\} \quad (\text{B.22})$$

$$F_H(\gamma\gamma \rightarrow ZZ) = \frac{2g_2^2 c_W^2 d_B}{M_W} \left\{ \frac{Z_{34}^B V_{12}}{D_H(s)} - \frac{2s_W^2 d_B}{M_W} \left[\frac{V_{13} V_{24}}{D_H(t)} + \frac{V_{14} V_{23}}{D_H(u)} \right] \right\} \quad (\text{B.23})$$

$$F_H(\gamma Z \rightarrow ZZ) = -\frac{2g_2^2 s_W c_W d_B}{M_W} \left\{ \frac{V_{12} Z_{34}^B}{D_H(s)} + \frac{V_{13} Z_{24}^B}{D_H(t)} + \frac{V_{14} Z_{23}^B}{D_H(u)} \right\} \quad (\text{B.24})$$

B.2 Higgs production processes

No single Higgs process due to \mathcal{O}_{UB} survives at high energy. We have only to consider two Higgs processes.

First the processes $V_1(\lambda)V_2(\tau) \rightarrow HH$ are described by 9 helicity amplitudes $F_{\lambda\tau}(\theta)$. Here θ is the angle between V_1 and H , and the normalization is such that the differential cross section writes

$$\frac{d\sigma(\lambda\tau)}{d\cos(\theta)} = C |F_{\lambda\tau}(\theta)|^2 \quad , \quad (\text{B.25})$$

where

$$C = \frac{1}{32\pi s} \frac{p_H}{p_{12}} \quad , \quad (\text{B.26})$$

includes no spin average. We find

$$\boxed{ZZ, \gamma\gamma, \gamma Z \rightarrow HH}$$

$$F_{\lambda\tau}(\theta) = -(1 - \delta_{\tau 0})(1 - \delta_{\lambda 0})(s_W^2, c_W^2, -s_W c_W) \cdot \left\{ \frac{d_B^2 g_2^2 s}{2M_W^2}(1 + 3\lambda\tau) + \frac{d_B g_2^2 s}{4M_W^2}(1 + \lambda\tau) \right\} \quad (\text{B.27})$$

and for the crossed channel

$$\boxed{HZ \rightarrow HZ, H\gamma \rightarrow H\gamma, H\gamma \rightarrow HZ}$$

These $HV_1(\tau) \rightarrow HV_2(\mu)$ channels are obtained by crossing those above. The helicity amplitudes are now given by

$$F_{\tau\mu}(\theta) = -(1 - \delta_{\mu 0})(1 - \delta_{\tau 0})(s_W^2, c_W^2, -s_W c_W)(1 - \cos \theta) \cdot \left\{ \frac{d_B^2 g_2^2 s}{4M_W^2}(1 - 3\tau\mu) + \frac{d_B g_2^2 s}{8M_W^2}(1 + \tau\mu) \right\} \quad (\text{B.28})$$

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